METEOROLOGICAL OFFICE
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THUNDERSTORM ELECTRIFICATION

1. Properties of thunderstorms

Thunderstorms may be regarded as electrostatic generators that produce positive and negative electrical charges; the positive charge being concentrated in one region of the cloud and the negative charge becoming concentrated in another. As physical separation of the charges of different polarity proceeds, the electric field and potential difference between the charge regions (or between one of them and the earth or ionosphere) grows until a lightning flash is initiated. At least part of the separated charge is neutralised by the discharge but the field builds up again and the sequence of events is repeated. A satisfactory theory must explain quantitatively how charge is generated, and separated at a sufficient rate to account for its dissipation in lightning flashes. It must account for the observed distribution of positive and negative charges and the observed changes of electric field produced by the discharges. The theory must also be consistent with the size and life cycle of the storm and its microphysical properties, represented typically by the scale, intensity and duration of the precipitation that accompany it.

Exploration by aircraft and radar reveals that thunderstorms generally consist of one or more 'cells' that contain strong vertical motions. Each cell grows, reaches maturity and decays. The growth stage lasts for about 10–25 minutes, is charaterised by updraughts of about 10 ms^{-1}, and the initiation of precipitation in the form of rain or hail in the middle troposphere. The onset of the mature stage coincides with the spread of precipitation towards the ground and the appearance of both updraughts and downdraughts, at least in the lower part of the cell. The mature stage lasts about 30 minutes. Lightning activity occurs predominatly during this phase. Thus any theory must be capable of generating and separating charge sufficient to supply the first lightning stroke within about 10 to 20 minutes of the appearance of precipitation of radar detectable size. This activity should be capable of being sustained for up to 30 minutes.

The cell may be about 1 km across when first detected by radar, but it usually develops rapidly up towards the $-20^{\circ}C$ isotherm and beyond, and extends to several kilometers in all directions. A feature some 10 km high and 8 km across results. The base of the thunderstorm is almost invariably warmer than $0^{\circ}C$, and the cloud top is often cooler than $-40^{\circ}C$. It is to be expected therefore that the cloud and precipitation contains both ice and liquid water forms.

2. Charge distribution in thunderstorms

The distribution of charge inside a thundercloud can be deduced from the variation of electric field at the ground caused by lightning flashes, as a function of distance from the storm. Early observation showed that there was a positively charged upper region and negative charge lower down.

The existence of a pocket of positive charge in the base of some thunderclouds has been inferred from ballon borne measurements of electric field. More recent measurements confirm this general picture as well as providing additional insight. The general structure of the charge distribution is shown in Figure 1.

During past few years ground based techniques have been utilised to locate some segments of a lightning flash. Radio interferometric techniques have been used for measuring the direction cosines of the centroid of discharges emitting VHF radio signals. The averaging period is approximatley 5 μs so that these centroids are likely to define discrete sources. An example of the positional detail provided by this technique is shown in Figure 2. In this example the discharges were marked by extensive horizontal developments before a more or less vertical discharge to ground was initiated.

Multisation measurements of the electric field change induced by lightning in New Mexico storms have also been made. A typical set of observations is shown in Figure 3.

The equivalent charge centres neutralised by the ground flash have been located from such field change data (see Figure 4). The field changes were found to be reasonably consistent with the lowering to ground of a localised, spherically symmetrical negative charge in the cloud. The centres of charge originated over large horizontal distance within cloud (up to 8 km) at more or less constant elevation between the -9 and the -17°C clear- air-temperature isotherms. Comparison with 3 cm radar measurements of precipitation structure, showed that the discharge developed through the full horizontal extent of the precipitating region of the storm and appeared to be bounded within its extent. In one instance where cellular structure of the storm was apparent, the strokes selectively discharged regions where the precipitation echo was stongest. The vertical extent of the charge locations was small in comparison with the vertical extent of the storm.

Such experiments suggest that the negative chage centres are located within a supercooled region of relativley small vertical dimension. They show also that the sources of negative charge lie within a relatively limited height range between the -10 and -25°C isotherms, and coincide predominatly with precipitation at these levels. Figure 5 shows a striking result from studies in Florida, New Mexico and Japan - where convective winter storms were investigated - that the temperatures at which the negative charge centres were located are similar in all three studies, even though the cloud bases are at very different pressure levels.

Bennetts et al reported measurements of electric field strength measured in aircraft traverses of convective cloud. The clouds, although electrically active, did not produce lightning. The data suggest that significant charge generation does not occur before the ice phase is present to a marked degree within the cloud. Nevertheless between two successive traverses through cloud, made in snow about -8°C some 4 minutes apart, fields of both signs increased by a factor of 4 to about 3 kVm^{-1} suggesting the significant charge separation is possible once ice is present. Figure 6 is a composition of electric field data obtained during 14 traverses of a cloud structure which reached -26°C. It is probable that features separated 'vertically' by more than 100 mb or so bear an evolutionary relationship to one another which is at least as important as that of their apparent spatial association. Nevertheless, some gross features of the charge distribution can be inferred. Thus between successive penetrations just above and below the -12°C isotherm, the vertical field changes sign on the southern, downshear side of the cloud, suggesting that a positive charge centre was located at this altitude. The measurements are consistent with the presence of a more diffuse negative charge below this region, but no substantial accumulations are indicated. The positive charge centre was located in a region bounded above by almost total glaciation in the form of ice crystals and below by a mixture of snow and hail. It is suggested that the circulation of the cloud, which probably generated at least two interacting cells during its lifetime of

over an hour, was insufficient to separate charges and maintain them within the cloud volume; if negative charge resides on precipitation much of it probably fell out of the cloud in that time. Nevertheless charge was being generated in the region of interaction between precipitation size particles and ice crystals; the very strong fields in the upper region of the cloud are consistent with positive charges on the latter.

Khriebel et al found that in one storm system for which Doppler derived wind field data had been obtained, the onset of lightning activity in one of the storm cells followed the development of s strong precipitation echo above the $0^{o}C$ level and coincided with a rapid ($25\ ms^{-1}$) increases in the speed of the updraught carrying this precipitation. Discharges in the vinicity and perhaps across the region of strong echo gradient were detected (see Figure 7).

From aircraft and ground based studies of thunderstorms it has been concluded that substantial charge densities ($5nC\ m^{-3}$) are carried on precipitation elements, over horizontal distances of several kilometres in the vicinity of the freezing level. The charges on individual elements are mainly, but noe exclusively, negative. No relationship was discernable between the size of particles and the charges they carried. Lightning activity within a cell was associated with upward motion of precipitation, and was evident where the precipitation rates did not exceed a few millimeters per hour.

The fact that the lightning discharges are strongly correlated with precipitation and that the source regions are found between about -5 and $-25^{o}C$ suggests that ice precipitation is a pre-requisite for significant charging rates. Observations made in thunderstorms capping the Zugspitze in Germany, reported that solid precipitation elements were dominant in the greater part of the thundercloud and were present on 93% of occasions. Snow pellets and pellets of soft hail were the most frequent form of hydrometeor, being present on 75% of occasions, and were always accompanied by strong electric fields, but large hail was relativley rare.

3. Charge separation mechanisms

The maximum fields around thunderstorms are observed to be about $4\ KVcm^{-1}$, the charge is typically 40 coulombs or more and some 5 to 10 coulombs are discharges in lightning stroke. The charge density must therefore be about 10 to 20 Ckm^{-3} or 10 to 20 nCm^{-3}. The evidence presented in the preceeding section is strongly suggestive of the role of small hail in carrying the charges that constitute the negative centre of a thunderstorm. In appears likely that the primary charging process or processes involve the collision of small hail with eihter supercooled droplets or ice crystals.

Wilson pointed out that an electrically polarised hydrometeor in falling through a cloud of ions or cloud droplets could, by a process of selective ion capture, acquire a net charge. Thus in a field acting to move positive ions downwards, a hailpellet becomes polarised with a net negative charge on the lower surface.

Negative ions are attracted to it, while positive ions are repelled. The rear surface has an equal positive polarisation charge of course, but if the terminal volocity of the particle exceeds the drift volocity of the positive ions, then the latter are not captured.

Thus the precipitation particle acquires a net negative charge. (see Figure 8) The fundamental requirement is that $V > K_+ E$ where V is the terminal velocity, K_+ is the positive ion mobility and E the electric field. V rarely exceeds $8^+ ms^{-1}$ for hydrometeors other than large hail, and for unattached ions $k \sim 1.5$ cm^{-2} s^{-1} V^{-1}. Thus the maximum field which can result from this process is ~ 0.5 kVcm^{-1}. Larger fields are possible in principle, through the capture of slow ions or charged cloud drops. Secondary sources of ions can be invoked but in general these tend to be productive only in the late stages of electric field growth.

The inductive theory of precipitation charging in which a cloud particle (radius, r_a) collides with the underside of a larger precipitation particle (radius, r_b) polarised in a electric field, and separates charge of magnitude proportional to the field strength (E), is an attractive one because of the inherent positive feedback between charge separation and field strength. The mechanism shown in Figure 9 has recieved considerable attention from modellers who have concluded that, in principle, water-water, water-ice as well as ice-ice collisions may separate charge at a sufficient rate.

The charge transfer (q) per bouncing interaction, if the large particle has charge Q_B is:

$$q = \frac{\pi^2}{6}\left(\frac{r_a}{r_b}\right)^2 \left[12\pi\epsilon_o r_b^2 E\cos\phi + Q_B\right]\left[1 - \exp(t/\tau)\right] \qquad (1)$$

where τ is the contact time and ϕ is the angle between the direction of the field and the radius to the point of contact. The maximum achievable charge on the precipitation element is:

$$Q_{MAX} = -12\pi\epsilon_o E r_b^2 \cos\phi \qquad (2)$$

However water droplet-raindrop collision experiments show that separation only occurs when the trajectory of the centre of the droplet passes the drop, otherwise they coalesce. The effective value of cos ϕ allowing bouncing is very small. Furthermore, experiments suggest that all collisions result in permanent coalescence for $E > 0.25$ kvcm^{-1}. Aufdermauer and Johnson showed that a small fraction ($\sim 0.1\%$) of supercooled droplets, colliding with a hailstone in the presence of an electric field, separate after a collision and transfer charge in accordance with the expression above. They suggested that these are likely to be glancing collisions, so again cos ϕ is likely to be small. In view of the high concentration of droplets and the fact that for aspherical hail pellets the aerodynamic and electrical 'equators' may be significantly different, it is not possible to discard the mechanism for ice-water inductive mechamism out of hand.

Although separation nearly always occurs following ice-ice collisions, leading to an average cos $\phi = \frac{2}{3}$, it is not obvious that the charges can flow through the ice during the available time of contact. Herizan theory for a collision between a 100 μm ice crystal and hailstone results in a contact time of $\sim 0.3\mu$s. The bulk resistivity of ice predicts a relaxation time of 10 ms and possibly a tenth of this if surface conductivity dominates. Practical evidence supports these ideas.

Rawlins carried out numerical modelling experiments testing the sensitivity of the inductive process to a number of microphysical assumptions, in a 3d model of cumulonimbus. He found that the electric field can reach breakdown threshold within half an hour of the appearance of precipitation, providng that the effect of multiple collision between ice crystals and hail pellets are neglected; these latter act to discharge earlier charge separation events. As it was found necessary to maximise the charging rate by invoking large numbers of small hail and ice crystal, this assumption may be questionable. The importance of the various inductive processes has therefore not been demonstrated unambiguously.

As water freezes on the surface of a hail stone, large potential differences may be developed across the ice-water interface, as a result of the selective incorporation of ions of one sign into the ice lattice. The sign and magnitude of the effect depends on the concentration of the ionic species. In most cases this generated negativley charged ice, so that rapidly growing hailstones, being able to freeze only a fraction of the impinging cloud water, acquire a liquid coat which is shed in the form of small positivley charged drops as shown in Figure 10. A similar result is expected to follow from splashing collisions, between hail and large drops.

The requirement of large hail, the low probability of splashing events and sensitivity to trace solutes make this an unlikely candidate for a universal charging mechanism. The effect may be swamped by inductive charging when the ambient field exceeds about 1 Vcm^{-1} since, because in most splashing events water is shed from the rear surface, the inductive process is dissipative.

Latham and Mason reported a process of charge separation associated with ice-splinter production during the growth of rime. The process depends on the fact that the concentrations of positive and negative ions in water increase quite rapidly with increasing temperature, and that the hydrogen ion diffuse more rapidly than the hydroxyl ion. Thus the cold end of a piece of ice acquires a greater fraction of positive ions (Figure 11a). It was suggested that a shell of ice would form around the outside of a supercooled drop soon after nucleation. It was conceived that the inside of the shell being at $0^{o}C$ and the outside of some lower temperature, would produce positively charged ice splinters as the shell thickened and fractured as freezing proceeded (Figure 11b). Unfortunately the mechanism requires unrealistically high rates of splintering to separate sufficient charge.

Results from laboratory experiments have been variable since the classical studies of Reynolds et al revealed large charging (hail pellet negative) when ice crystals and supercooled droplets coexisted in the cloud through which a hail pellet moved. It has been shown that, over a crystal diameter range of 10 to 300 μm, the charge transfer was roughly proportional to the square of the ice crystal diameter. Laboratory studies suggest that charge carriers are actually present on the contact interface and do not flow along the surface - thereby avoiding the time constant problems of the inductive theory. Such charge transfer is possible in collision between particles having different surface work functions. Charge transfer takes place to establish the required contact potential. At present there is no time-dependent theory for this, but experiments confirm that charge transfer can take place. Calculations suggest that a charge transfer of about 10^{-14} - 10^{-13} C is required per collision to provide the necessary charging rate. As the capacitance of a 100 μm sphere close to plane surface is about 10^{-14} - 10^{-13} farad, the required difference in surface potential is between 0.1 and 1 volt. Such potential differences are believed to exist between

evaporating and condensing drops or between rimed and non rimed ice (see Figure 12). The potential differences are of the correct sign to produce negatively charge hail pellets when these are riming in the region colder than about -10°C and colliding with unrimed vapour grown crystals. Such a mechanism fits the observations described earlier very well qualitatively, but more work is necessary to confirm this quantitatively, and to elucidate the physics of charge transfer.

4. Lightning

The most common producer of lightning is cumulonimbus cloud. However lightning also occurs in snow storms, sand storms and in the clouds over erupting volcanos. Very little is know about the latter and almost all of the following discussion will be based upon discharges from cumulonimbus. Such lightning can take place entirely within a cloud (intracloud or cloud discharges), between two clouds (cloud-to-cloud discharges) or between a cloud and the earth (cloud-to-ground discharges). Although the most frequnt occuring form of lightning may not be the cloud to ground discharge, the greater part of the literature is concerned with it.

A cloud-to-ground lightning flash, which typically lasts about 0.5 s , is usually composed of several intermittent discharges called strokes, each of which has a duration of milliseconds. A stroke, in turn, is made up of a leader phase and return stroke phase. The leader initiates the return stroke by lowering the cloud charge (usually of negative sign) and cloud potential towards the earth. First or stepped leaders are heavily branched and carry charges of a few coulombs; dart leaders which precede subsequent strokes carry less charge and follow the main channels of previous strokes.

The negatively charged region of the thundercloud provides the negative charge which flows to ground in the cloud-to-ground flash. If it is assumed to be isolated and sperical within a radius a, then a lower limit can be estimated for a, by requiring that the maximum field (to be found at it boundary) is less than the breakdown field of the atmosphere. This varies inversely with pressure and is about 21 KV cm^{-1} at 3 km or 30 KV cm^{-1} at sea level. In practice, cloud lightning is initiated at a much lower threshold $\sim$ 4KV cm^{-1}. A typical value for the negative charge is -40 coulomb so that

$$a^2 \geq Q/4\pi\epsilon_0 E_{MAX} \quad \therefore \quad a \geq 1\ km \tag{3}$$

It is evident that the lightning process must be able to drain charge in less than 1s from a volume of about 4 km^3.

A similar analysis can be carried out, in a cylinderical volume, for the minimum leader radius. If the leader is typically 5 km or so in length, its charge per unit length must be $\sim 10^{-3}$ coulomb/m to contain the typical charge of 5C dissipated in each stroke. Assuming a maximum field of 30 KVcm^{-1}, $a_{leader} \geq \rho/2\pi\epsilon_0 E_{MAX}$, $\therefore a_{leader} \geq 6m$. The luminous radius is likely to be less than this as the existence of charge does not guarantee the emission of radiative energy.

The potential of an isolated sphere of radius 1 km and carrying a charge of 40 coulombs is

$$V = \frac{Q}{4\pi\epsilon_0 a} \approx 3 \times 10^8 \text{ volts} \tag{4}$$

The presence of the earth's surface reduces this but the order of magnitude of the potential difference between ground and charge is $\sim 10^8$ volts. Thus the energy available for dissipation is $\sim 4\ 10^9$ joules. A single lightning stroke brings ~ 5 coulombs to ground. If the channel is 5 km long the energy dissipated per metre is $\sim 10^5$ joules m^{-1}. This is capable of vapourising some 40 g of water per metre in buildings, trees or people! In the atmosphere the energy is converted to dissociation, ionisation, excition and kinetic energy of the channel particles, to the energy of expansion of the channel and to radiation.

5. Initiation of lightning

Since the breakdown field in dry air, at normal atmospheric pressure, in the absence of particles, is about 30 KV cm^{-1}, while the largest fields that have been recorded within thunderstorms are about 4 KV cm^{-1}, some initiating process must be invoked. In recent years it has become clear that the emission of corona from the extremities of hydrometres is a very likely candidate for this.

For a pointed electrode, the discharge process begins in a small volume near to the tip, where the local electric field is high enough to permit ionisation of the gas molecules by any stray electrons. These latter must have been accelerated sufficiently by the electric field operating over their mean free path so that their kinetic energy exceeds the ionisation potential of the gas. Such activity releases further electrons at each subsequent collision. This process of cumulative ionisation is know as an electron avalanche, and is at the root of all forms of corona discharge. The threshold for corona reduces with reducing pressure as the mean free path increases.

The possibility that positive corona is emitted form the surface of a raindrop, highly deformed by strong electric fields, has been studied in considerable detail. Large drops were suspended in a vertical wind tunnel in the presence of an electric field, and it was shown that corona occurred from pointed regions of drops. These regions resulted from hydrodynamic instability under the influence of strong electric forces. The lower surface of the drops tended to be flattened by aerodynamic pressure and corona were initiated from the rear surface as shown in Figure 13. For uncharged drops of radii greater than 2 mm the critical onset was about 9.5 KV cm^{-1}, somewhat greater than the Taylor instability value for drop disruption. If the drops carried a high charge of the appropriate polarity the threshold corona field was reduced to about 5.5 KV cm^{-1} and somewhat lower if the field was inclined to the vertical. However, even under the most advantageous conditions, the corona fields were higher than the maximum fields observed in thunderstorms.

Griffiths and Latham have examined the possibility that ice hydrometres may emit coronas. They demonstrated that corona currents of both signs can be initiated at low threshold fields from ice specimens in the form of needles and plates, prisms and artificial hailstones provided the temperature is warmer than a critical value, which is fixed by the electrical conductivity of the ice surface. This critical value is $\sim -18^{\circ}C$ for natural ice hydrometers (see Figure 14).

Crabb and Latham studied the possibility that the collision of a pair of raindrops within a thundercloud may produce momentarily, a grossly deformed object whose shape is particulary conductive to corona onset. They found corona at fields as low as 2.5 KV cm^{-1} for glancing collisions and about 5 KV cm^{-1} for central collisions. Of course such events are probably rather rare and transitory. Nevertheless, the authors suggest that one such event per m^3 per minute is likely in precipitation of about 20 mm hr^{-1}.

Given that positive corona is likely to be produced on hydrometeors in the regions of strong field that is close to the edge of the charged region perhaps enhanced by the positive charge how does this initiate the stepped leader? The direction of these coronas is directed along the local field lines; upwards in the region between the charge centre and ground as shown in Figure 15. By comparison with observations of such discharges from power lines, it has been suggested that highly branched streamers expanding laterally and toward the negative charge centre result. The streamers adopt a broadly conical form. The net upward movement of positive charge effectively increase the negative charge in the vicinity of the original coronas site at though such charge had been lowered from above. New corona streamers in the regions below are then promoted by the resulting field enhancement. The net result is a growing conical volume. In the process, charge from the upper broad end of the cone is lowered and concentrated towards the earthward apex with the consequent field enhancement there to reach the breakdown field of 30 KV cm^{-1} and promote the propogation of a negative streamer; the first step of the stepped leader.

6. The discharge processes

Any theory devised to describe the stepped leader should take account of its observed characteristics. Namely

(i) the minimum average velocity for negatively charged downward leaders is about 10^5 ms^{-1},

(ii) the steps are typically 50 m in length, with a pause time between steps of $\sim 50\,\mu s$,

(iii) some 5 coulombs of negative charge are deposited over the length of the leader, requiring a current of about 100 amps flowing for a few tens of milliseconds.

It has been suggested that the leader is formed by negative corona streamers as shown in Figure 16(a). These die out rapidly except in the strongest fields so that radial and peripheral branches do not develop. The stepped nature of the leader is a further manifestation of this tendancy to dissipate. Qualititativley it is possible to view the process as one which lowers negative charge and the potential of the negatively charged region. Although the channel is conducting, charge is distributed along it and the quantitative nature of the process has not been worked out. When a stepped leader is within a few tens of metres of the ground, an upward propogating positive streamer may result. When the junction is complete the first return stroke is initiated.

The negativley charged leader, which may have a tip potential of 10^7 to 10^8 volts with respect to the earth, is effectively short circuited to ground. Ground potential is then propogated up the channel. The intense electric field present between the ground potential and the negative charge potential forms a wavefront and the negative charge potential at a third to a tenth of the velocity of light, making the trip between ground and cloud in about 70 μs. The excees negative charge deposited on the leader channel is lowered to ground in the form of mobile electrons (Figure 16(b)). The current measured at the ground rises typically to 10 to 20,000 A in a few microseconds, and falls to one half of the peak value, typically in 20 to 60 μs. Currents of the order of hundreds of amps may continue to flow for several milliseconds.

When the very sharp voltage gradient reaches the source regions of negative charge, most of the charge from the channel must have passed to ground. The stroke current therefore reduces. However the proximity of earth potential to the negative region can initiate a new era of drainage by upwards positive streamer action as before. This drainage then funnels a new wave of negative charge from the area of propogating streamers to the relatively confined but somewhat decayed conducting channel of the previous stroke. This sweeps down the channel, presumably as a streamer but in a continuous fashion, if this takes place in a time less than about 100ms. The degree of ionisation increases and charge is again deposited in the channel; albeit to a lesser extent than by the stepped leader. Cloud potential is carried earthward once more to initiate a new return stroke as shown in Figure 16(c).

7. Special forms of lightning

Bead or chain lightning is a visually well documented phenomenon in which the lightning channel breaks up or appears to do so, into luminous fragments generally reported to be metres to tens of metres long. The beads appear to persist for a longer time than does the usual cloud to ground discharge channel.

Various theories of bead lightning have been proposed. Perhaps the most plausible is that the phenomenon is due to a pinch effect instability by which the current carrying channel is distorted into a 'string of sausages' with the stong light emission coming from the necked off regions of high current density.

Ball lightning is the name given to the mobile luminous spheres which have been observed, usually during thunderstorms. A typical ball lightning is said to have the dimensions of an orange or grapefruit and a lifetime of a few seconds. The literature consists, in general, of either complications of eye witness reports or attempts to explain how these reports may be explained by some combinations of physical processes. As far as is known, no-one has succeeded in generating a ball lightning, or made measurements on such phenomena other than by reception and interpretation of light emitted by the object - most of which have been in real time! Some attempts have been made to place bounds of energetics of ball lightning distruction by inspection of damage caused. The fact that such damage does occur suggests that the phenomenon is not always an optical illusion; as has been claimed. Nevertheless these is no known theory to explain how a luminous sphere capable of a lifetime of several seconds can move rather slowly horizontally and vertically, apparently of its own volition, and disappear either silently or explosively.

8. Thunder

It is generally accepted that thunder is the result of intense, rapid heating of the lightning channel to form a high pressure shock wave which degenerates into a loud audible sound at large distances. In work carried out at the New Mexico Institute of Mining and Technology and reported by Holmes et al, data recorded by a network of microphones have been analysed to display the joint temporal and frequency distributions of sound energy shown in Figure 17.

The general characteristics of such plots are the wide-band tongues of intense sound indictative of so called thunder 'claps', superimposed upon low frequency 'rumbles'. The presence of significant energy at a few Hz is also apparent.

9. Effects of lightning

It is to be expected that aircraft often intercept cloud/cloud flashes as well as those from cloud to ground. Very little is known about the former, but it is usually assumed that the currents are not greater than those of typical ground strokes. As a lightning leader approaches an aircraft, high electric fields are to be expected at sharp points and edges. The high fields give rise to streamer discharges which propogate away from the aircraft until one of them contacts the approaching leader. Further development of the stepped leader away from other extremities is then envisaged until a branch reaches ground or another charge centre. Thus an aircraft receiving a strike always exhibits at least one entrance and one exit point. However an aircraft moves a significant distance relative to a stationary lightning channel in the time taken for a flash to be completed. When a forward extremity forms the initial attachment point, reattachement to small imperfections on the conducting surface passing through the channel can take place. This process can produce a number of discrete attachment points corresponding to successive strokes down stream of the initial point.

Two sorts of damage to aircraft are to be expected; one results from the energy dissipated in structure due to the high current. For a given current this energy is a function of resistance, so efforts are expended to ensure the lowest possible imepdance between aircraft structures by efficient bonding. The other sort of damage is a consequence of the high peak current and its high rate of change – which can appraoch 80 $KA\,s^{-1}$. This produces strong, varying electromagnetic fields which can disturb and/or damage electrical apparatus. Again, 'low impedance-at-high-frequency' bonding and the enclosures of sensitive components in shielded structures are sought for protection.

Annual deaths in England from lightning and Wales have been between 1 and 6 per 10 million of the population since the 1920s. Death from lightning results when current through the heart or respiratory centre causes them to malfunction. The body acts as a structureless gel for the sort of currents which result in death or injury so that the position of the points of exit and entry play a crucial role in defining the current path and hence whether or not the heart or brain are at risk. It is not certain whether cardiac or respiratory arrest are a function of charge or energy dissipation but almost certainly the threshold is often not reached until the low current stage, which occurs following the establishment of an external arc around the body.

When a tree is struck, people or aninals beneath it may be at risk from induced effects. The electrical impedance of a tree trunk to the lightning current is a complex function of many variables but between the ground and the height of a person, it is thought to be typically a few kilohms compared with a typical body resistance of one kilohm. A person standing alongside the trunk is at earth potential. As current through the trunk increases, a point may be reached when the potential drop across the lower part of the trunk exceeds the breakdown potential between the trunk and person. A side flash results as in Figure 18(a). Obviously this phenomenon can occur in a number of situations and provides a mechanism for injury of people within buildings and possibly for multiple deaths when a strike occurs to several individuals in a crowd. Figure 18(b) shows how an ohmic and inductive current may result in a person standing beneath a tree.

A direct strike to open ground results in current flow into the surrounding earth. This creates potential gradients in the soil/rock around the strike point which are proportional to the current density and earth impedance. Feet in contact with the ground can be at a different potential resulting in current through the body. Such currents are unlikely to be fatal to bipeds but may pass through the hearts of animals causing death (Figure 18(c)).

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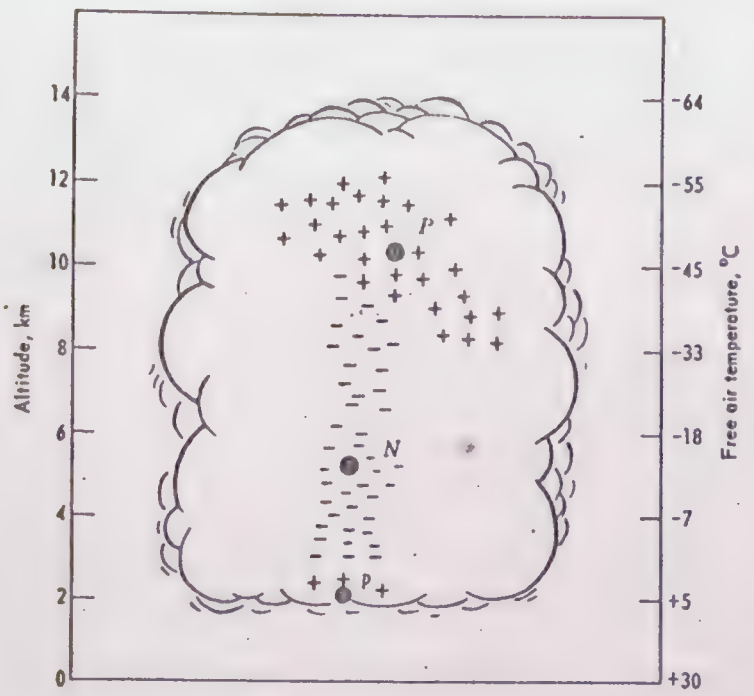


Figure 1 Distribution of electric charge in typical sub tropical storms.

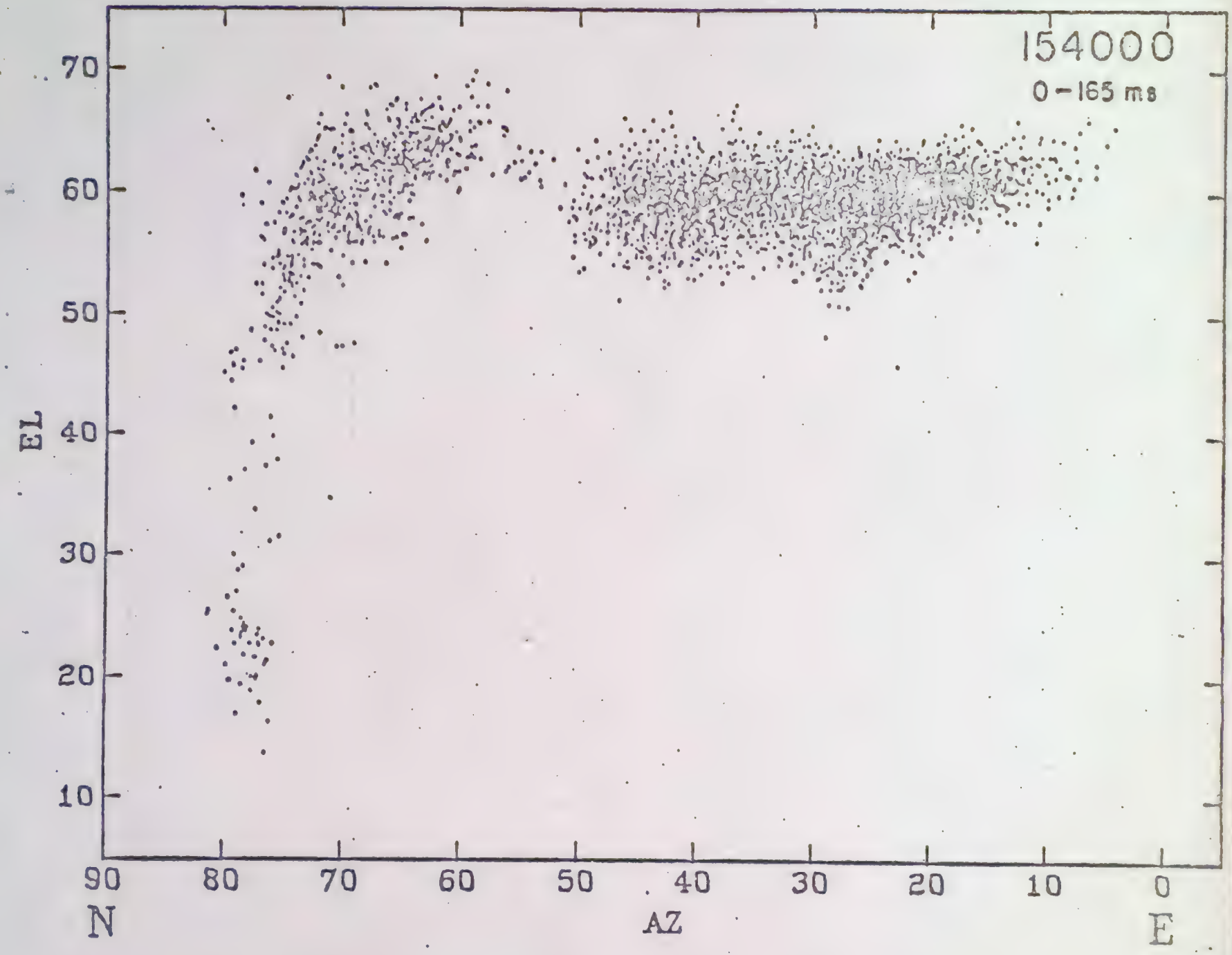


Figure 2 Azimuth (AZ) and elevation (EL) angles in degrees of individual radiation sources for initial portion of a lightning flash.

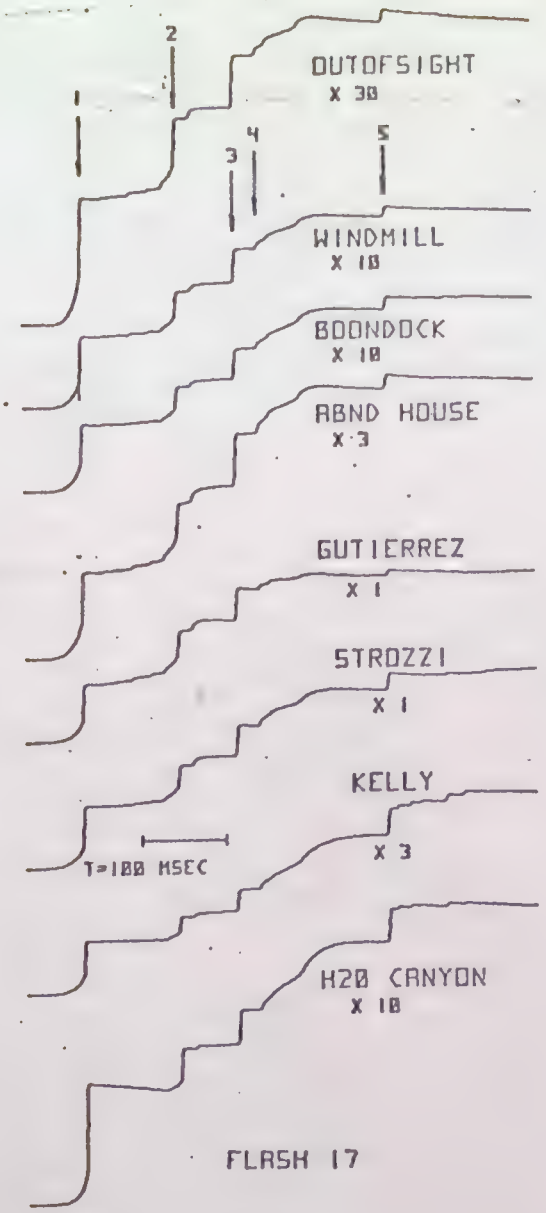


Figure 3 Electrical field changes measured at several stations during a single lightning flash.

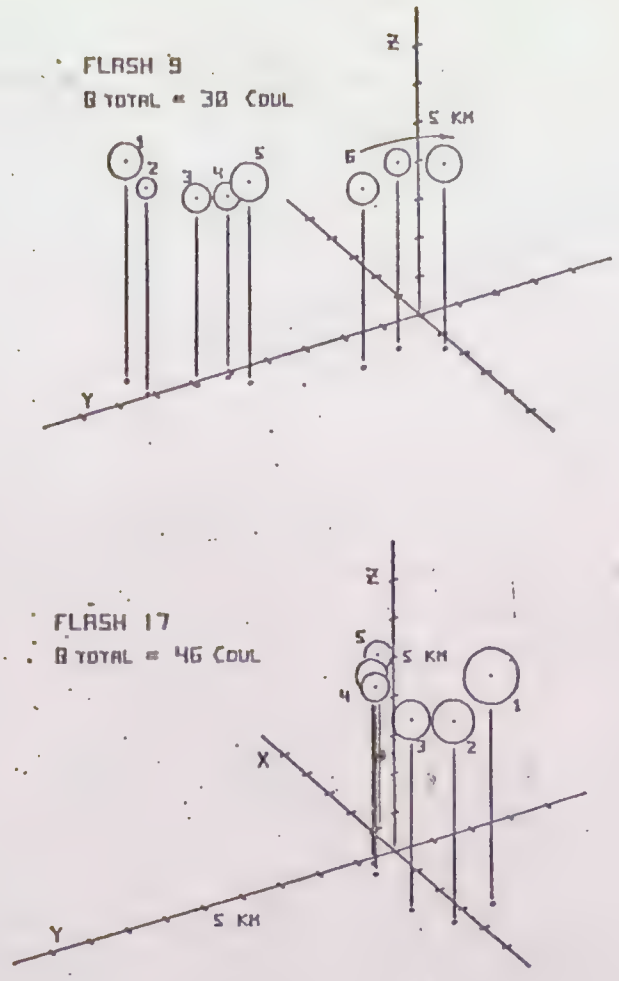
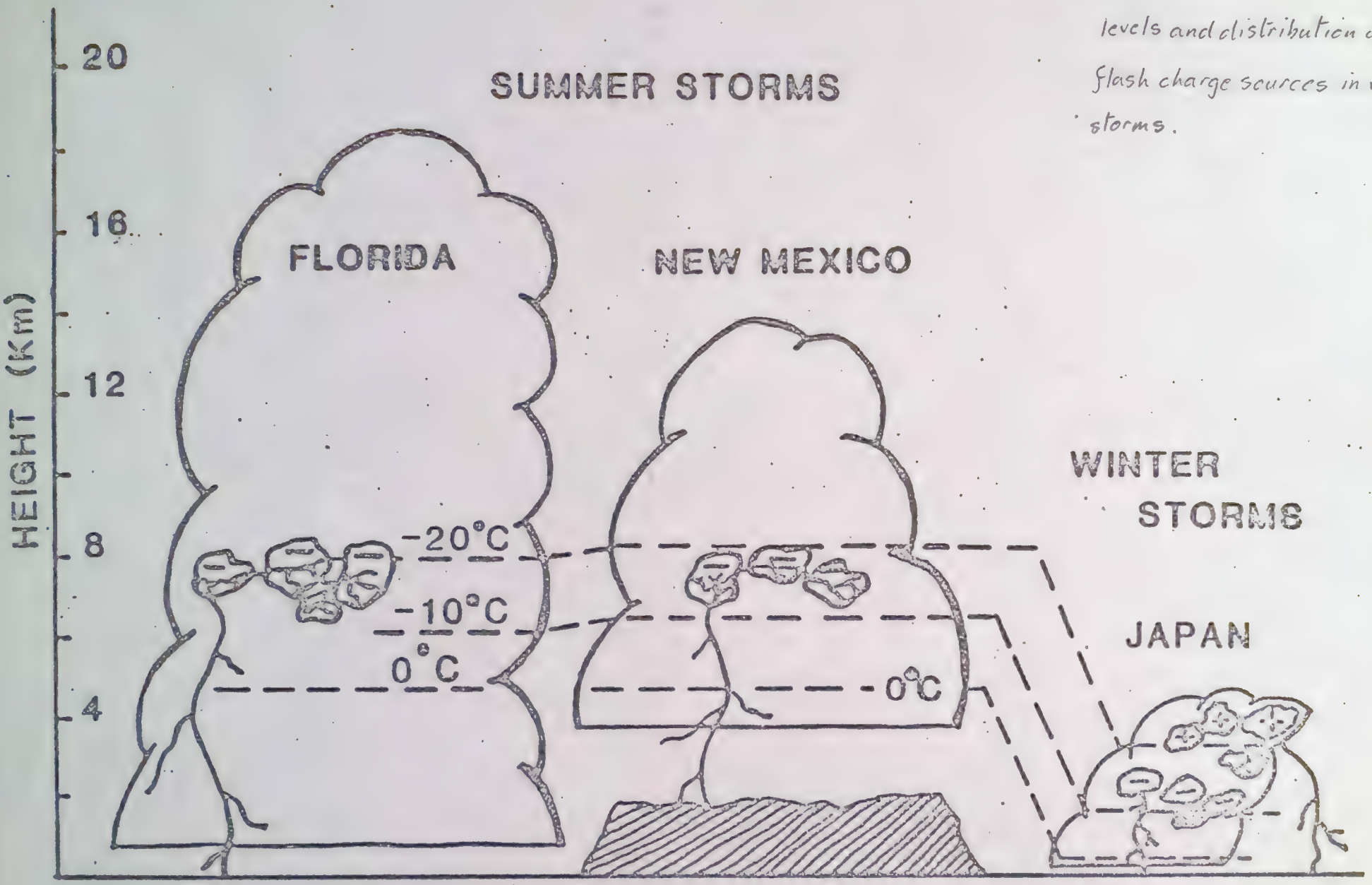


Figure 4 Inferred charge distributions giving rise to individual lightning flashes. Field change data for flash 17 are shown in figure 3. Circles denote the size of spherical volumes containing individual stroke charges assuming charge density 20 $C\ km^{-3}$.

Figure 5 Schematic diagram showing levels and distribution of ground flash charge sources in various storms.



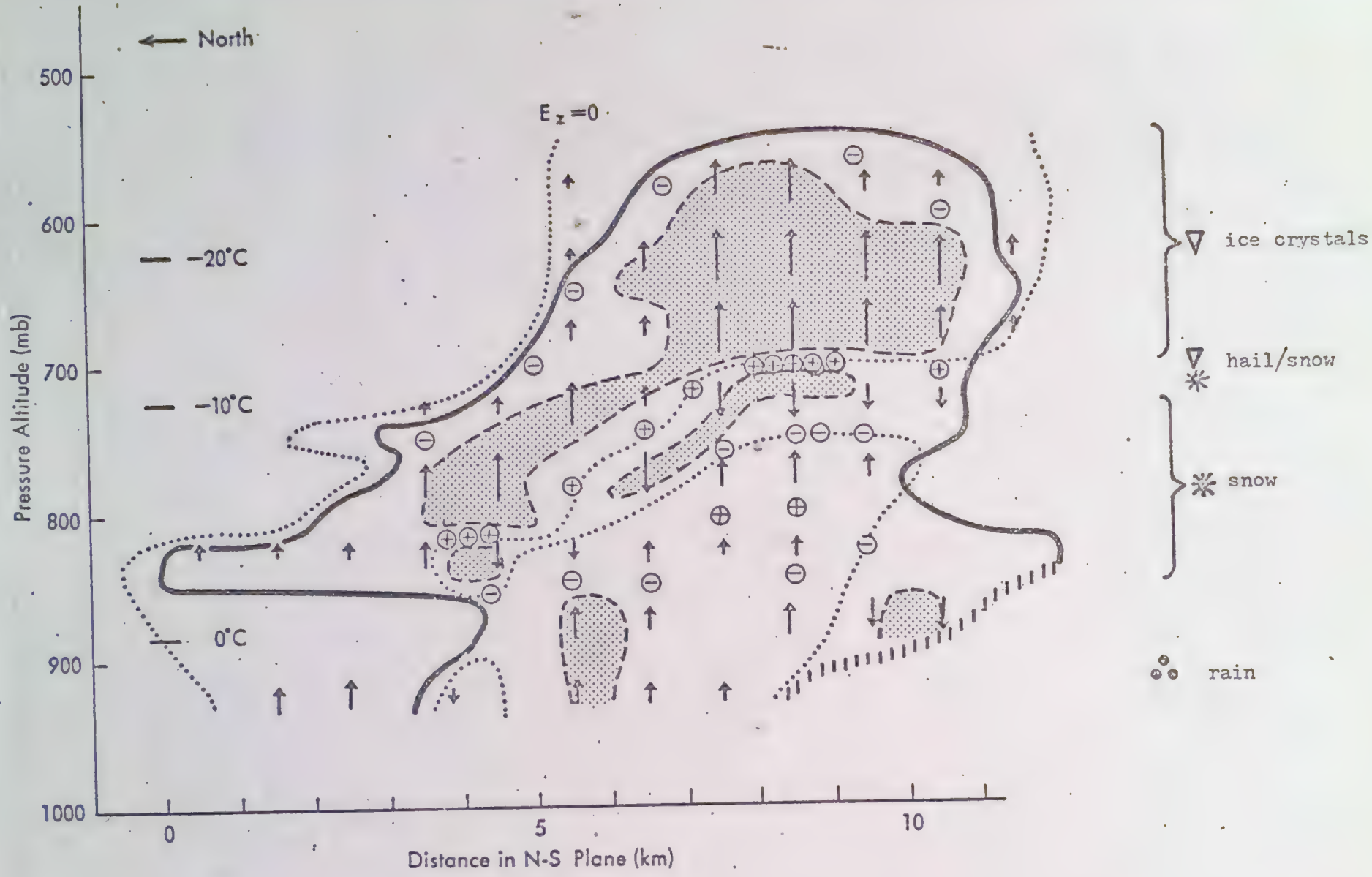


Figure 6 Distribution of vertical component of electric field in cumulonimbus cloud. No lightning was observed and fields were derived from aircraft measurements. Arrows denote sense and magnitude of electric field. Shading denotes field > 32 kV m^{-1}.

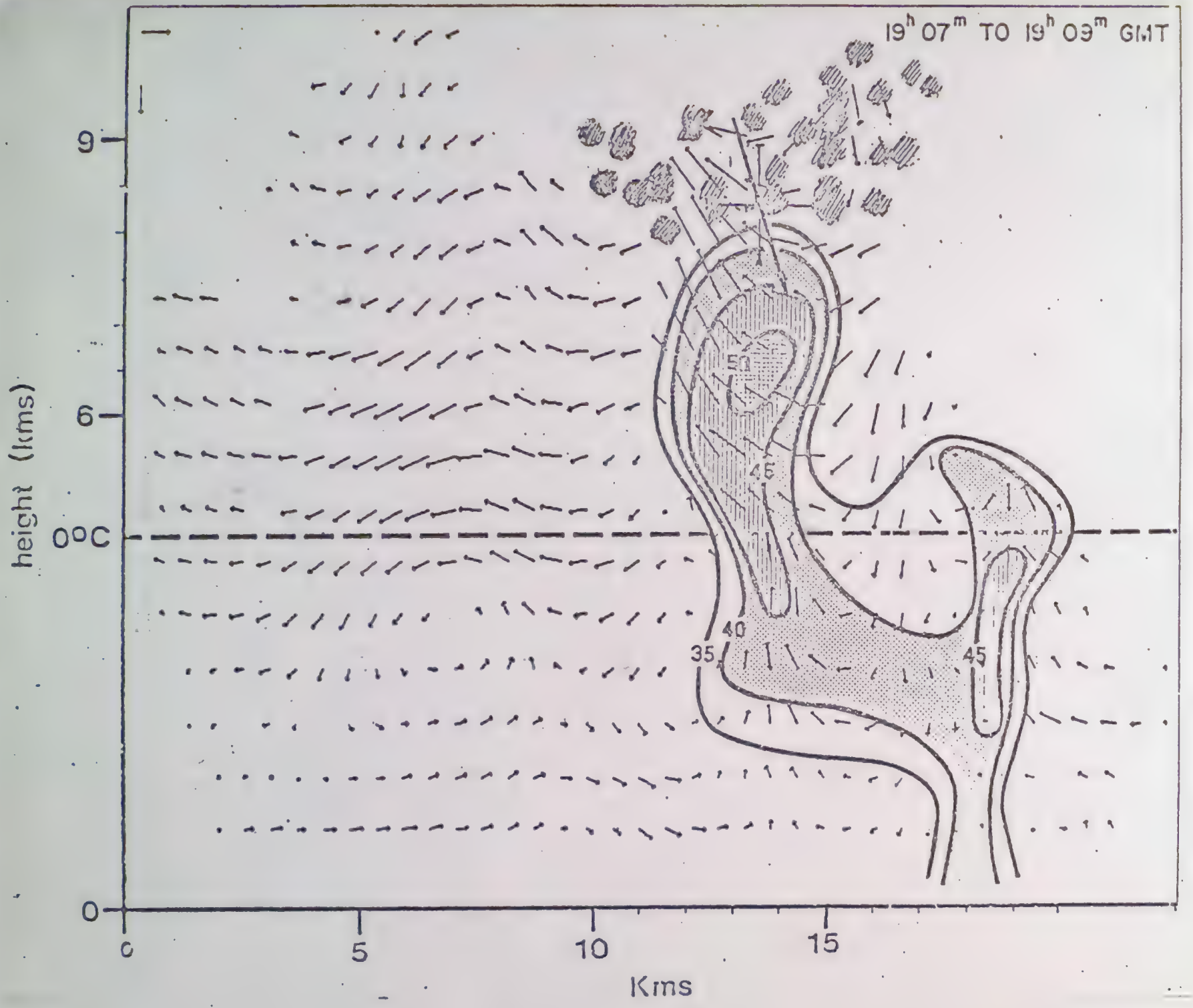


Figure 7 Radar reflectivity contours and Doppler wind field in an electrically active cloud. Hatching denotes radiation sources for discharges at a similar time.

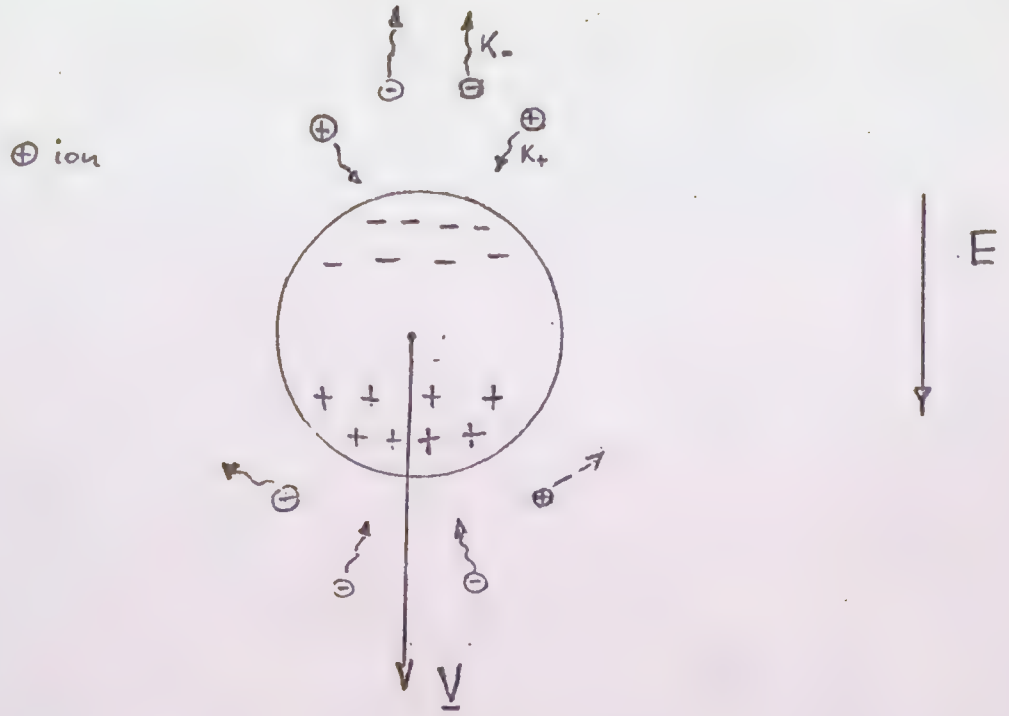


Figure 8 The ion capture mechanism for a polarised droplet falling in a vertical electric field. Negative ion mobility is much greater than positive ion mobility.

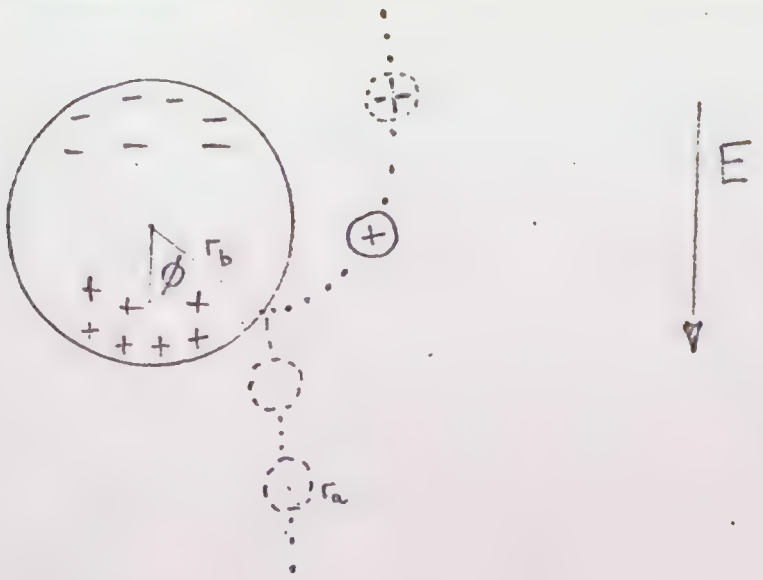


Figure 9 The inductive charging mechanism for a particle of radius r_b falling through a vertical electric field. Particles of radius r_a contact the larger particle but bounce off.

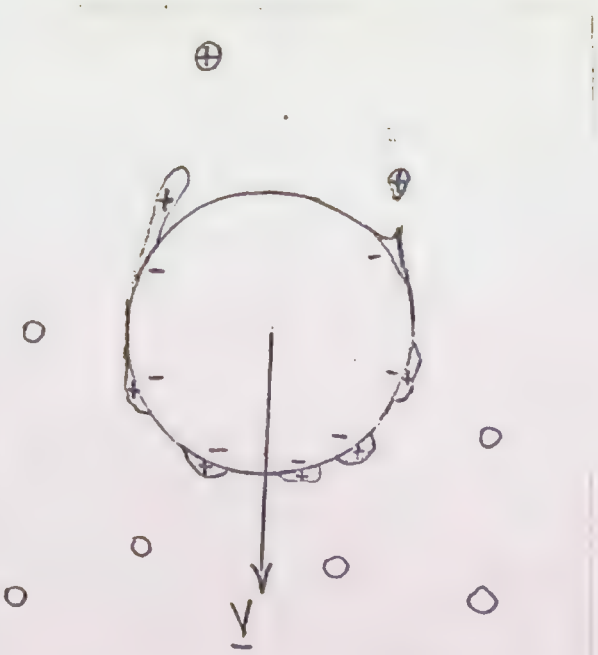


Figure 10 Charging by a mechanism involving charge separation across a water-ice interface during freezing. Supercooled water drops partially freeze on impact with a falling ice particle but some water is shed from the rear of the particle.

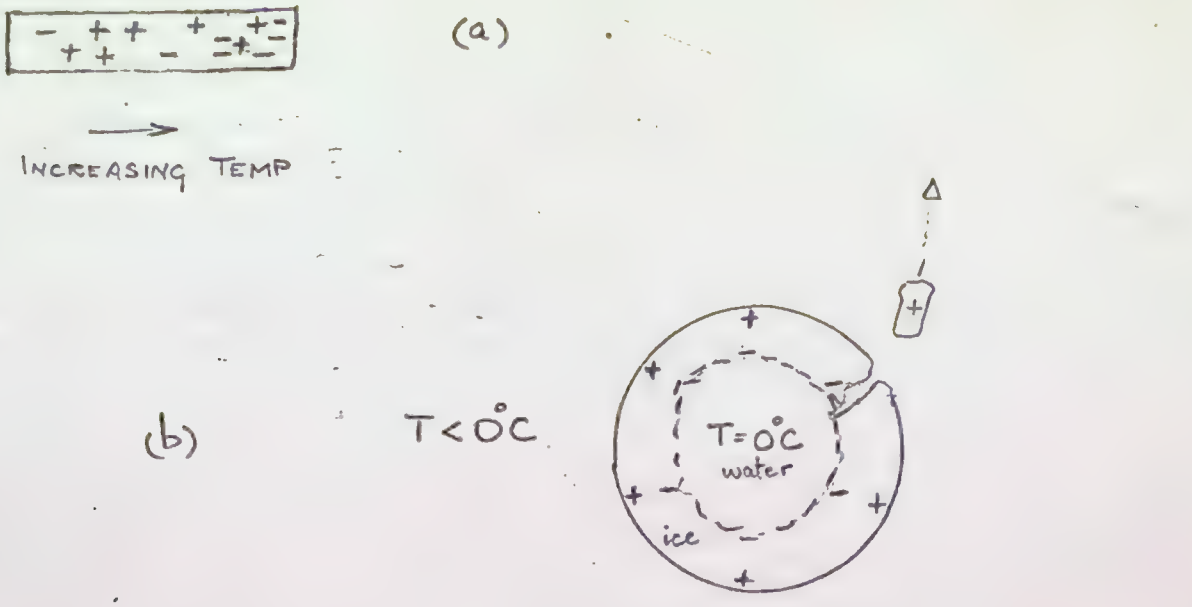


Figure 11 The temperature gradient theory of charge separation

(a) Distribution of charge carriers in ice subject to a temperature gradient. Hydrogen (+) ion mobility exceeds that of negative ions.

(b) Ejection of charged splinters during the symmetrical freezing of a water drop. Air temperature < 0°C, interior temperature = 0°C.

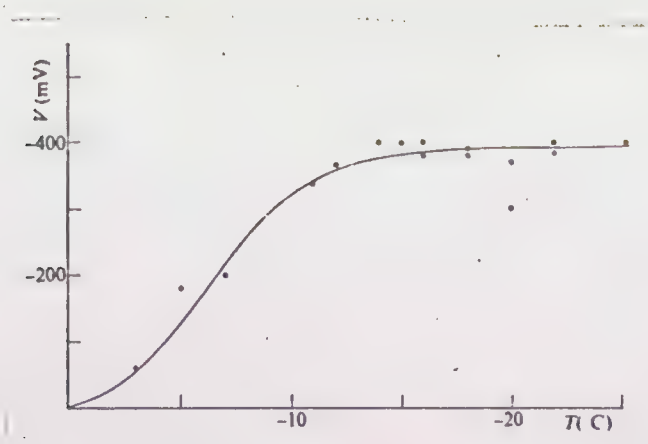


Figure 12 Change in surface potential of ice after riming as function of temperature T. Results obtained from laboratory experiments assign potential of 0 V to unrimed ice surface.

Figure 13 Instability of a 2mm radius drop in a slowly increasing vertical electric field. Frames are 2·5 ms apart, time increasing to the right of the diagram. The formation of an upper surface point which suddenly collapses can be seen. The drop was freely falling at terminal velocity.

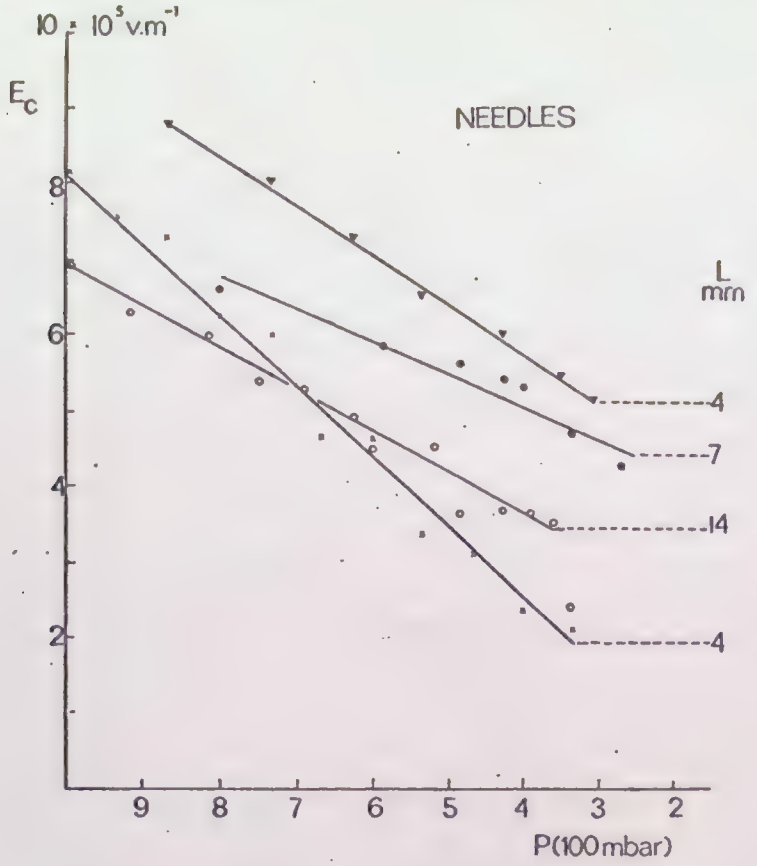


Figure 14 Measurements of the critical field E_c for the formation of corona discharge from ice needles of length L. The pressure dependence of E_c is shown. Observations were made at -12°C.

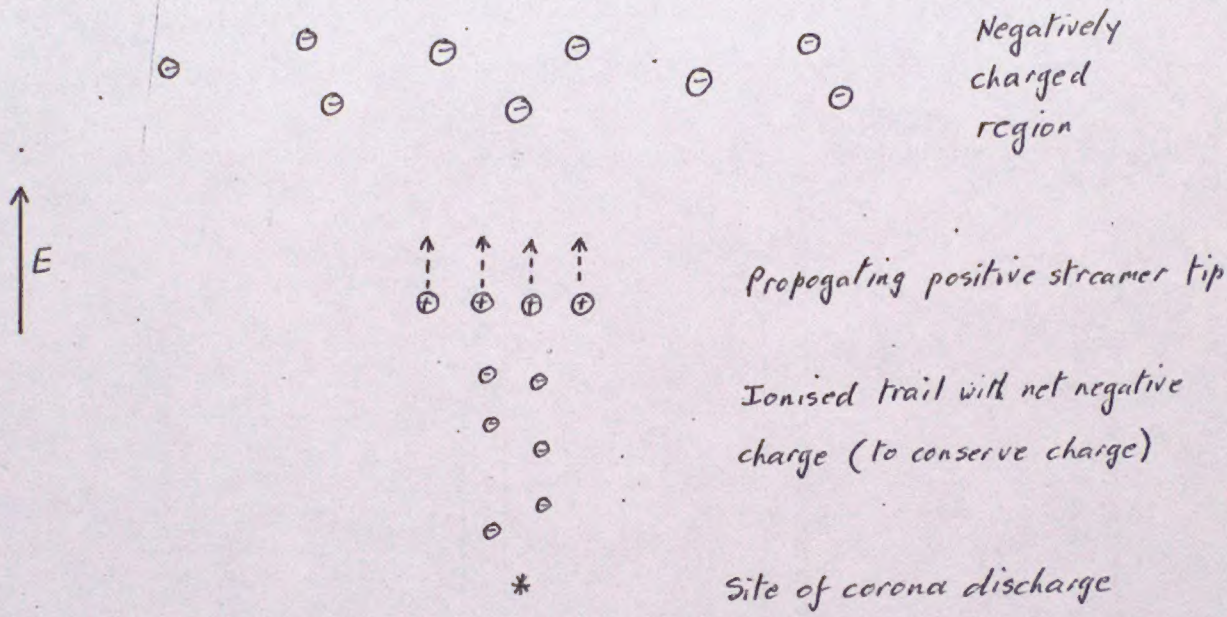


Figure 15 Initiation of lightning stroke from a corona discharge below the region of negative charge.

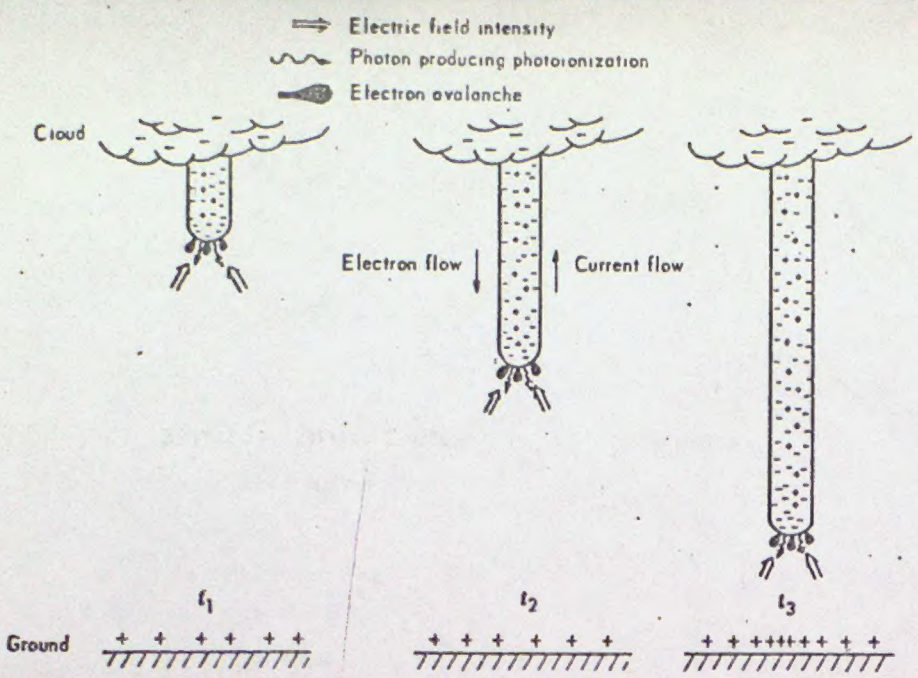


Diagram showing general features of streamer mechanism as applied to lightning leader into virgin air in absence of step mechanism. The times $t_3 > t_2 > t_1$.

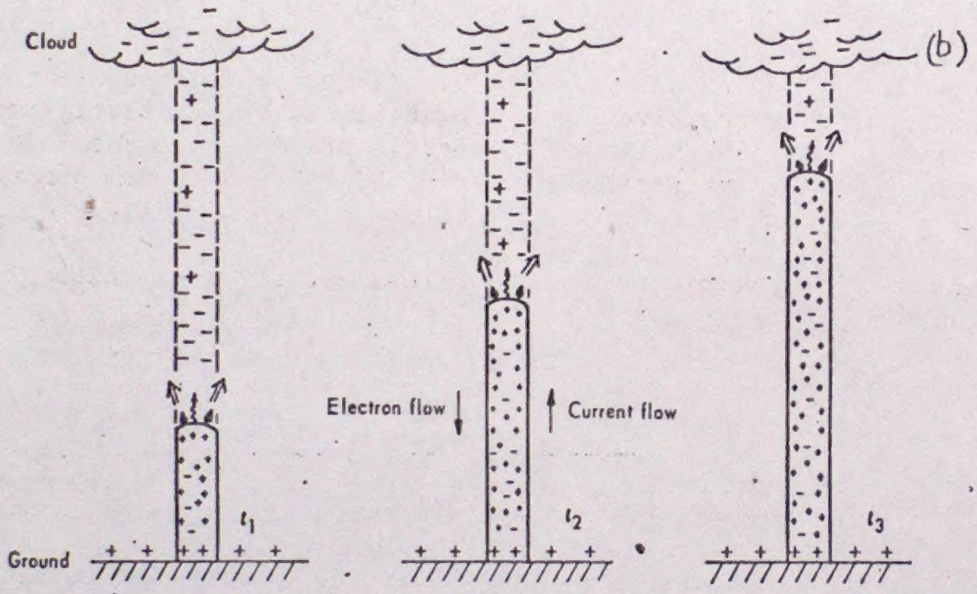


Diagram showing general features of streamer mechanism as applied to return stroke. Times $t_3 > t_2 > t_1$. Note that all current is carried by electrons since the mobility of positive ions is low.

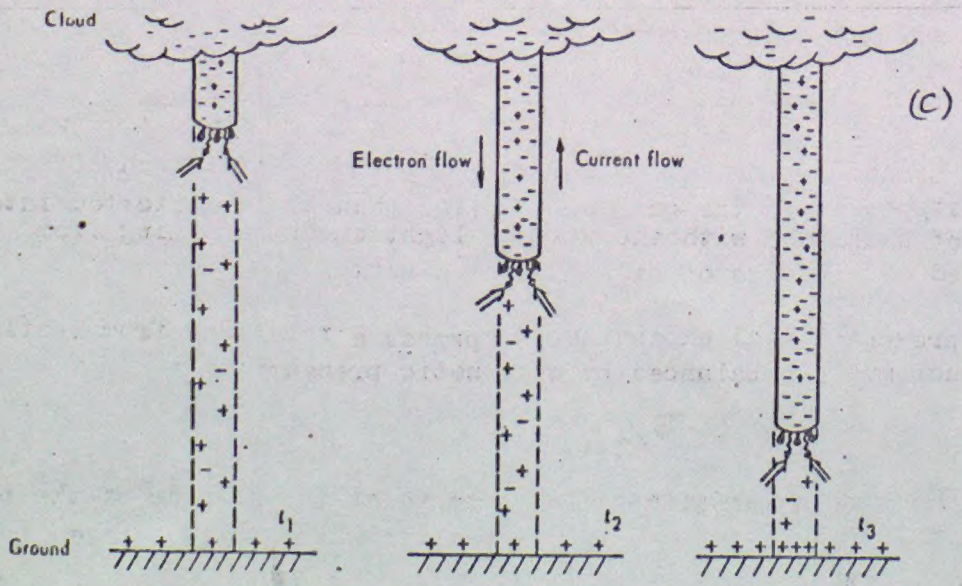


Diagram showing general features of streamer mechanism as applied to dart leader. The times $t_3 > t_2 > t_1$.

Figure 16 Schematic diagram showing the mechanisms for the various parts of the lightning flash

(a) stepped leader

(b) return stroke

(c) dart leader.

The dart leader - return stroke may be repeated several times during the flash.

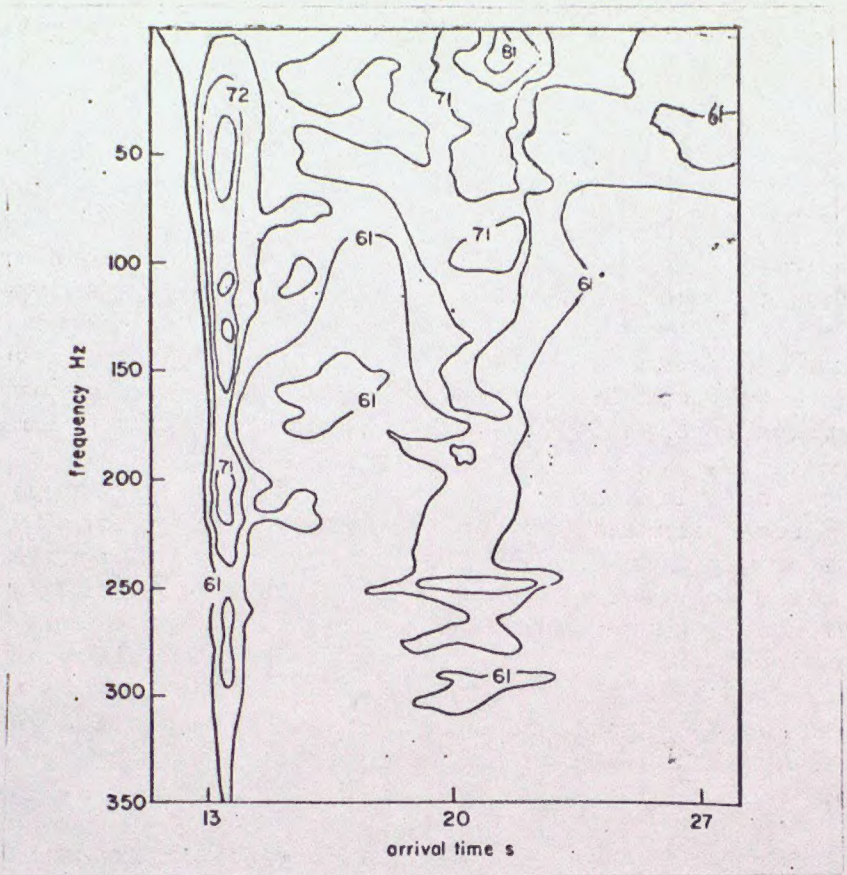
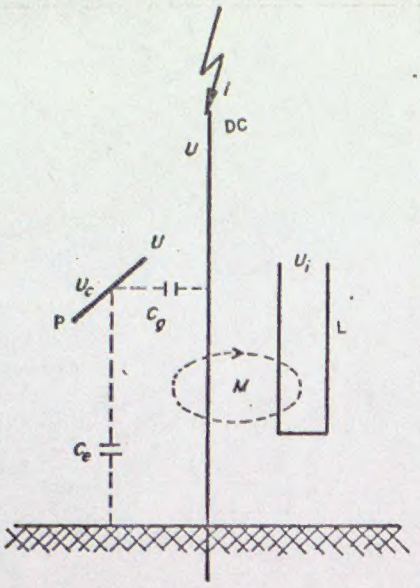
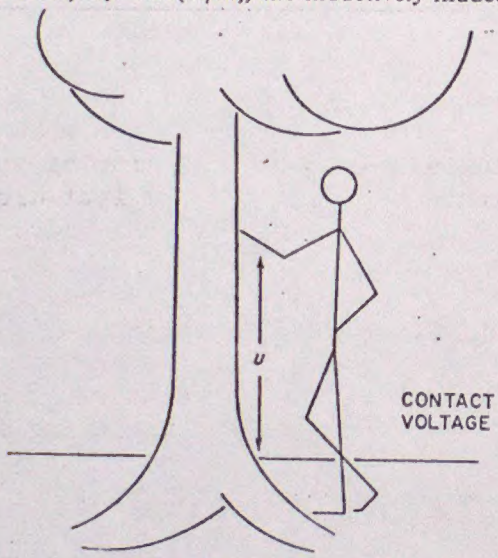


Figure 17 Distribution of the frequency components and their amplitude through a thunder roll. Contours of amplitude (arbitrary units) are shown. The results show the intense, broard frequency, thunderclap followed by lower intensity rumbles. The significant energy at frequencies of a few Hz is evident.



Inductive effects of the lightning current; i = lightning current, U = voltage of down conductor, DC = down conductor, P = isolated metal component with capacitance C_p to down conductor and capacitance C_e to earth, $U_c = UC_e/(C_e+C_p)$ capacitatively induced voltage on P, L = metallic loop with mutual inductance M to down conductor, $U_i = M(\mathrm{d}i/\mathrm{d}t,)$ the inductively induced voltage.



Contact voltage: $u = i(R+R_e)+L\,\mathrm{d}i/\mathrm{d}t+u_s$, where, i is current flowing through the tree, R is the resistance of the tree between the highest point of the body touching the tree and earth, R_e is the "effective" earthing resistance of the tree, L is the inductance between the highest point where the body touches the tree and earth, and u_s is the potential drop between the bottom of the tree and the feet.

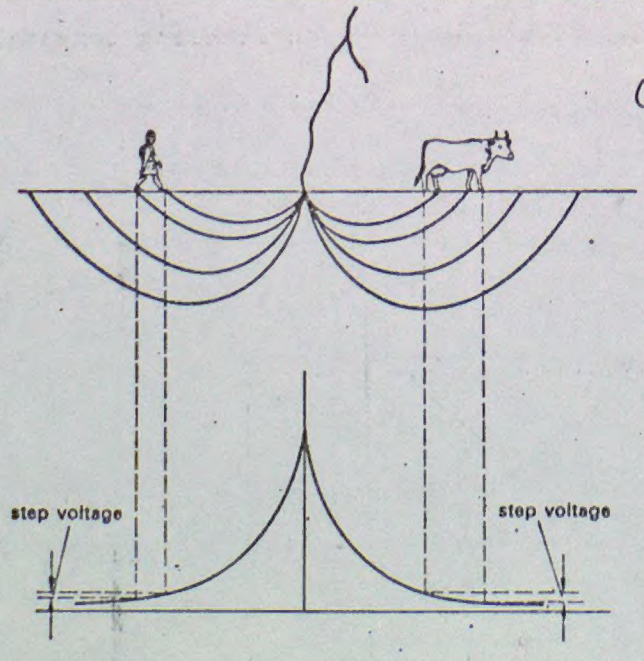


Figure 18 Schematic diagram showing effects of lightning discharges to ground.

(a) Inductive effects may cause high fields in objects close to the discharge path

(b) Contact with a resistive path to ground can give rise to high fields

(c) The field induced at the surface may result in large fields between two contact points. This can drive fatal currents through the hearts of 4 legged animals.